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An AIR PYCNOMETER for Forest and Range Soils

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INTRODUCTION

Accurate assessment of total porosity of forest and range soils is often difficult, due to varying volumes of incorporated organic matter (humus, roots, and larger organic fragments) and the heterogeneity of soil minerals, particle sizes, and stone content. These problems are particularly apparent in forest and range soils where incorporated organic matter of surface soils varies from traces to over 20 percent and diverse soil parent materials and soil-forming processes exist.

A frequently recommended procedure for estimating total soil porosity (Richards 1954, Wilde and Voigt 1955, Black et al. 1965) suggests calculation from the bulk density and an assumed or determined particle density. This equation is:

$$St = 100 \frac{P_p - D_b}{P_p}$$

where St is percent total porosity, P_p is particle density, and D_b is bulk density. This calculation may result in considerable error of porosity estimate if (1) incorporated organic matter is high, (2) the heterogeneous mixture of soil minerals departs significantly from the assumed particle density, or (3) the estimation of bulk density is influenced by soil shrinking or swelling with moisture content change. Both (1) and (2) above result in an error in the estimation of particle density and (3) results in an error in the estimation of bulk density.

Direct determination of porosity of undisturbed soil cores eliminates many of the above sources of error. Many investigators have designed and used various types of air pycnometers (Kummer and Cooper 1945, Nikolayev 1965, Russell 1950, Torstensson and Eriksson 1936, Visser 1937) for direct determination of porosity based on the application of Boyle's law of gases.^{1/}

Various means are used to obtain and measure air pressure, but in each case, calibration of the instrument is required. Basically, these instruments use two chambers of approximately equal volume, one of which is an air reservoir at known pressure; the other will contain the soil sample. Air pressure in the reservoir is increased to some exact value, usually between 1 and 2 atmospheres; then a valve is opened allowing pressure to equilibrate in both chambers. Resultant pressures can be read on pressure gages, mercury manometers, or as a change in head of either mercury or water in a capillary tube. Page (1948) and Kummer and Cooper (1945) suggest the use of sensitive

^{1/} These pycnometers apply the principle of Boyle's law of gases which states, "If the temperature of a confined gas does not change, the product of the pressure and volume is constant."

air pressure gages and include a discussion of the advantages of air pycnometers for determining both total soil porosity and distribution of soil pore sizes.

Although these references all apply the same principle for determining porosity, none adequately describes the apparatus relative to sizes of air chambers and soil sample or to accuracies expected with air pressure gages; neither do the references consider particular problems of forest and range soils.

This paper describes the use and calibration of an air pycnometer that may be used for rapid determination of either pore space and size distribution or bulk specific gravity of undisturbed cores of forest or range soils.

THE AIR PYCNOMETER

The air pycnometer has three component air systems (fig. 1): (A) a fine adjustment system, (B) a constant volume reservoir, and (C) a soil sample chamber. The constant volume reservoir and soil sample chamber have approximately equal volumes of 130 to 140 cc. each. The fine adjustment chamber has a volume of about 30 cc., sufficient to adjust the pycnometer over plus or minus a half pound of pressure at 14 pounds per square inch (p. s. i.). Dimensions of the soil sample chamber were set to accommodate a 100-cc. undisturbed soil core in a sample ring approximately 2-1/4 inches in diameter and 1-1/2 inches high.

In operation a sample soil core is placed in the sample chamber with the aid of a handling tray (see center of cover photograph). Valve 3 (fig. 1) is closed and pressure in the constant volume reservoir and fine adjustment system is increased to approximately 14 p. s. i. with a hand airpump. Valve 1 is closed, and the fine adjustment system is used to adjust the pressure in the constant volume reservoir by a standard procedure of always increasing pressure to above 14 p. s. i. and then reducing the pressure to exactly 14 p. s. i. Valve 2 is then closed and the soil sample chamber closed. When Valve 3 is opened, pressure in the sample chamber and constant volume reservoir equilibrate. Calibration of pressure readings is required to determine volumes of solids in the soil sample chamber. The soil sample chamber and related components of the pycnometer were constructed with sufficient metal to act as a heat sink to maintain constant temperature.

Calibration

A special ring was constructed so water could be conveniently used for calibration and accuracy checks. The calibration was made by addition of measured volumes of water to the special ring.

Exact volumes of the sample chamber and constant volume reservoir were calculated by Boyle's law from the equilibrium air pressures at 0 and 100 cc.

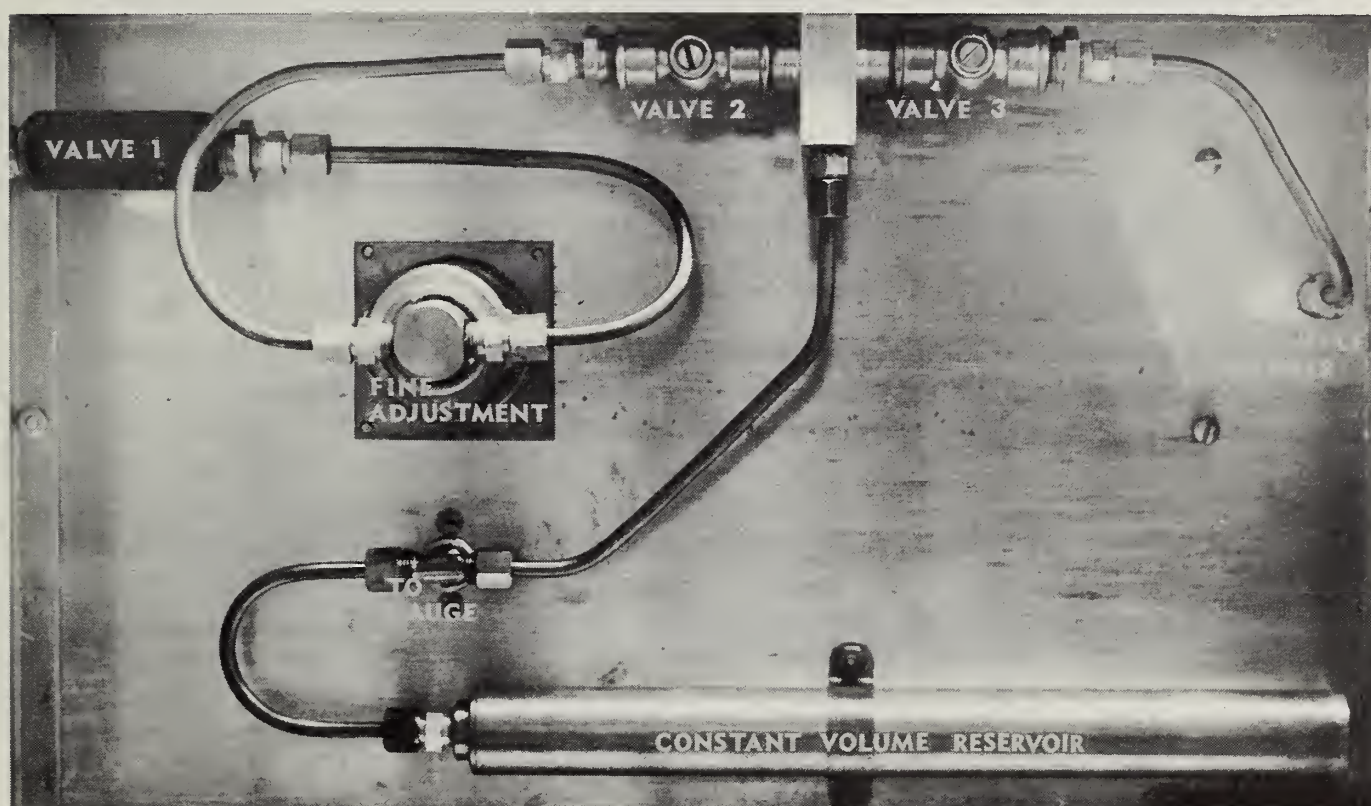
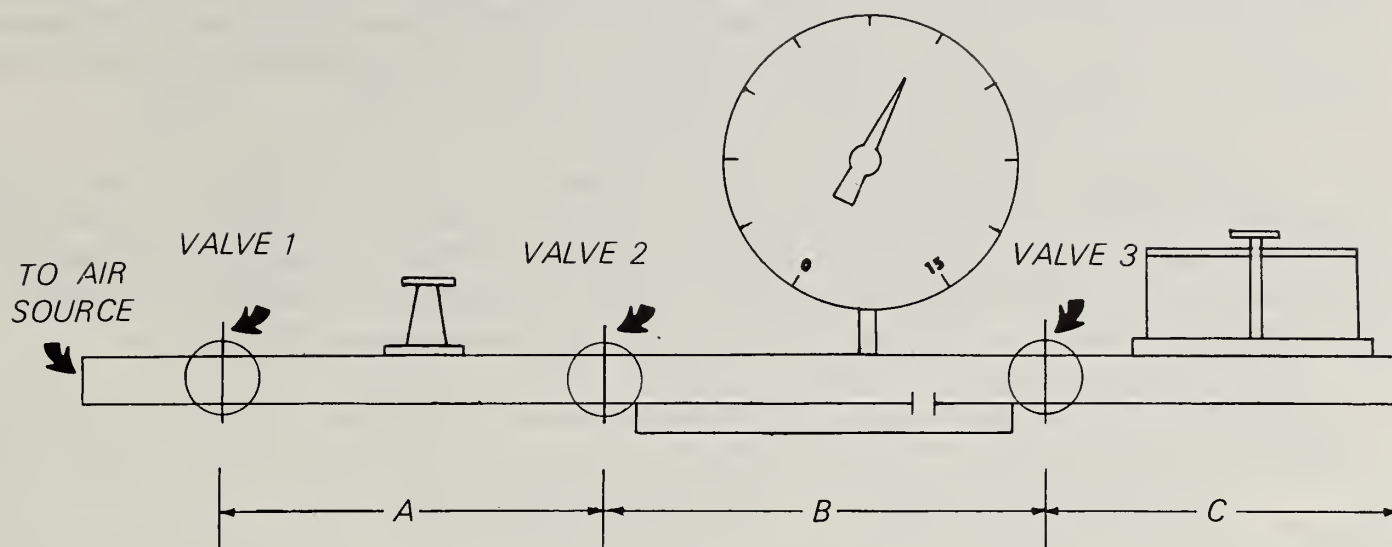


Figure 1.--Schematic drawing of component systems of the air pycnometer,
 A. Fine adjustment system
 B. Constant volume reservoir
 C. Soil sample chamber

Photograph shows working portion (underside) of the pycnometer.

of volume in the soil chamber. Zero volume in the soil chamber included the handling basket, soil core retainer ring, a rubber band, and bottom cheese-cloth cover--only soil was omitted. The 100-cc. pressure reading included the same items, except that the special ring was filled with 100 cc. of water.

In the following equations, P_1 is the initial pressure (14 p. s. i.) in constant volume reservoir which is V_1 (system B in fig. 1). P_2 is the pressure at zero volume, and V_2 is the combined volumes of the constant volume reservoir and soil sample chamber ($B + C$). P_3 is the pressure when 100 cc. of the soil sample chamber is occupied by solids. Relationships of these are:

$$P_1 V_1 = P_2 V_2 \quad \text{at zero volume of solids,}$$

$$P_1 V_1 = P_3 (V_2 - 100) \quad \text{at 100 cc. of solids.}$$

Therefore,

$$P_2 V_2 = P_3 (V_2 - 100)$$

or,

$$V_2 = \frac{P_3 (V_2 - 100)}{P_2}$$

with actual pressure readings substituted for zero and 100 cc. of volume:

$$V_2 = \frac{11.48(V_2 - 100)}{7.25}$$

$$V_2 = 271.53 \text{ cc.}$$

When we are solving for V_1 .

$$P_1 V_1 = P_2 V_2$$

$$V_1 = \frac{P_2 V_2}{P_1} = \frac{7.25(271.53)}{14.00}$$

or $V_1 = 140.65$ cc., the volume of the constant volume reservoir. These values were used to calculate pressures equivalent to actual volumes of solids for comparison with the calibration.

Pycnometer Determinations

Total porosity is determined on air-dry soil cores. These results are corrected for water content and reported on an oven-dry weight basis. Soil

samples in 100-cc. core rings are air-dried in the laboratory adjacent to loose samples of the same soil. Loose soil samples are oven-dried to determine correction factors for air-dry to oven-dry moisture content.

Also, use the pycnometer to find the distribution of pore sizes by allowing saturated soil cores to equilibrate on a tension table or pressure membrane at varying tensions or pressures. After total porosity has been determined, the amount of water may be calculated by a weight change or determined directly on a volume basis by the pycnometer.

To find bulk specific gravity of soil matrix material, divide oven-dry weight of the soil core by the total volume of soil solids in the core sample. Calculate soil bulk density in the usual manner based on the weight of the soil material in the 100-cc. core sample.

Sources of Error

Some investigators (Vicente-Chandler et al. 1956, Jamison 1953) have reported errors in soil porosity determinations by pycnometer methods. A prime source of error (Jamison 1953) is adsorption of air on soil colloids in clay soils when moisture content is reduced below air-dry. Other errors in pycnometer methods were attributed to (a) solution of air under pressure in the moisture film around soil particles, (b) air leakage in the system, (c) changes in atmospheric pressure, and (d) changes in the pycnometer calibration with use.

Tests of the pycnometer for air leaks, stability of calibration, and effects of change in barometric pressure were made routinely during a year of regular use. Any air leaks would reduce air pressure below 14 p. s. i. on the gage when the sample chamber and Valve 1 were closed. Several standard samples of varying volumes were used to check the stability of the calibration curve and effects of changes in atmospheric pressure. Solution of air in moisture films around soil particles was checked from air dry to saturation by adding known volumes of water to air-dry soil cores (also determined by changes in the weight of soil core) and rechecking the volume of solids by the pycnometer.

RESULTS AND DISCUSSION

Quantitative determinations of soil properties must be evaluated for accuracy and precision^{2/} of methods as well as inherent variation between like soil samples. Accuracy of the pycnometer method for determining or

^{2/} Accuracy is defined as the ability of the method to estimate the true value. Precision is the ability of the method to reproduce the same answer under given test conditions.

reproducing volumes of known standards is excellent as indicated by the stability and accuracy of the calibration curve and duplication of values for repeated determination on standards. Table 1 shows an average deviation, 0.16 cc. or 0.4 percent, for comparison of actual volumes with pycnometer-estimated volumes with Boyle's law used to calculate pressure.

Table 1.--*Comparison of actual solid volumes with calculated values from Boyle's law and pycnometer calibration*

Actual volume	Pycnometer- measured volume	Deviation volume	Deviation from actual
<u>Cubic centimeter</u>	<u>Cubic centimeter</u>	<u>Cubic centimeter</u>	<u>Percent</u>
10.0	9.99	0.01	0.1
20.0	19.90	.10	.5
30.0	29.83	.17	.6
40.0	39.36	.64	1.6
50.0	49.89	.11	.2
60.0	60.00	--	--
70.0	70.12	.12	.2
80.0	80.29	.29	.4
90.0	89.98	.02	.02
--	--	<u>1/ .16</u>	<u>1/ .4</u>

1/ Average.

Results of 18 pycnometer determinations made on a standard of glass beads at varying atmospheric pressure over a 1-year period are shown in table 2. The low coefficient of variation (0.3 percent) indicates excellent duplication over a normal range of atmospheric pressure change. Repeated determinations on the same standard or soil sample always gave equally precise results. The higher coefficients of variations for replicated core samples of forest soils (table 2) indicate largest sources of variation arise from real differences in soil matrix.

Table 2 also gives data on mean total porosity for replicated soil samples for six forest soils in a range of textural classes. Clay content ranges from 3 percent in the Entiat River fine-gravel loam to 25 percent in the Mission Creek clay loam. The Jack Creek pumicite has a uniform silt texture, whereas the pumice soil has numerous water-washed pumice particles up to about 1 cm. in diameter. These pumice particles will float for a short time and are often considered to have trapped air space; however,

results in table 3 show a specific bulk density of 2.86. This high value would indicate that under normal soil conditions all the soil pore space is available for moisture storage.

Table 2.--*Variation in pycnometer determinations
of total soil porosity*

Item	Number of samples	Mean total porosity	Coefficient of variation
		<u>Percent</u>	<u>Percent</u>
Glass beads, 18 determinations	1	58.8	0.3
Sand Creek (loamy sand):			
A horizon	18	54.7	6.0
B horizon	18	50.1	3.8
Mission Creek (clay loam)	12	48.4	7.2
Icicle River (silt loam)	8	52.6	3.2
Entiat River (fine-gravel loam)	6	51.4	3.8
Jack Creek (pumicite)	5	60.4	6.8
Pumice soil	8	73.7	2.0

Table 3.--*Variation in bulk density and bulk specific gravity
as determined by the pycnometer*

Item	Number of samples	Bulk density		Bulk specific gravity	
		Mean	Coefficient of variation	Mean	Coefficient of variation
		<u>Grams per centimeter</u>	<u>Percent</u>		<u>Percent</u>
Sand Creek (loamy sand):					
A horizon	18	1.14	8.0	2.53	1.7
B horizon	18	1.28	4.0	2.56	.7
Mission Creek (clay loam)	12	1.35	7.4	2.61	2.3
Jack Creek (pumicite)	5	1.06	10.7	2.70	1.5
Pumice soil	8	.75	4.7	2.86	1.4

Variation in bulk specific gravity and bulk density is also shown in table 3. Bulk density is inversely related to total porosity. Mean bulk specific gravity of soil particles is considerably less variable than most other soil properties as indicated by low coefficients of variation. Figure 2 presents average results of checking 18 soil cores with moisture contents ranging from 3 percent (air dry) to 40 percent.

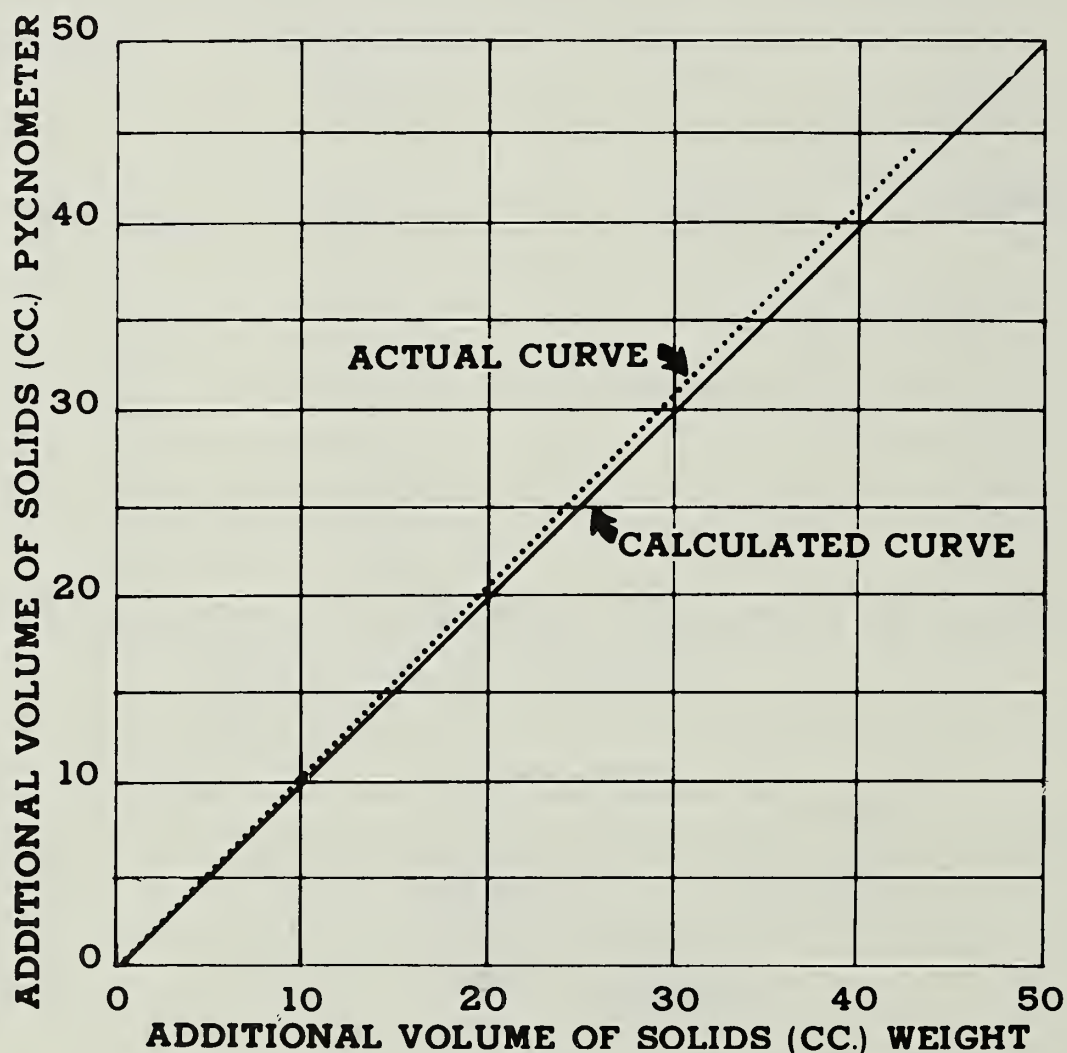


Figure 2.--Increasing the volume of solids by adding known amounts of water to a soil resulted in a slight departure of the actual pycnometer-measured curve as compared with the calculated curve.

The slight overestimation of solids by the pycnometer (fig. 2) suggests either trapped air or slight swelling of soil organic or mineral colloid constituents caused by water saturation. Observations indicate a change in volume of soil particles with change in moisture content. As specific gravity of soil particles is usually determined in water, the lattice structure of expanding soil particles would have maximum dimensions under these conditions. Rich and Thomas (1960) point out that, in polar liquids, certain expanding-lattice clays will swell to volumes many times their dry volume. This phenomenon is generally considered to result from differences in interlayer spacing caused by changes in hydration. Clays which are dominantly montmorillonite (such as the hurricane clay studied by Jamison (1953)) possess this characteristic to a much greater extent than kaolinites.

Grim (1953) cites several investigators who have presented evidence showing that water held on the surface of clay particles may either be denser (as high as 1.7) or lighter (0.73) than normal water. A gram of water is assumed to occupy 1 cc.; however, if orientation and arrangement of water molecules on surfaces of clay colloids causes a gram of water to occupy more or less than 1 cc. of volume, then allowances for volume change based on a water weight change would erroneously estimate the volume of solids.

In view of the above sources of difficulties in determining certain soil properties containing clay-water systems, it would seem desirable to prescribe standard moisture conditions of soils, particularly soil high in colloidal clays. Bulk density, bulk specific gravity, and total porosity should be determined when clay fractions are in a completely hydrated state. This state would correspond to the standard technique of determining real specific gravity of soil particles in water.

Although the above considerations are important to soil physicists, they are of little concern in much of the forest and range soils research. Clay contents of these soils seldom exceed 30 percent of the less than 2 mm. fraction. Inherent differences in mineral and organic composition and texture of soils usually contribute most of the variation in total porosity estimations.

SUMMARY

The air pycnometer described has been used for several years to assess total porosity and macro- and micropore space of forest and range soils. Procedures used are rapid, and results are precise and reproducible. Observations and certain results indicate the physical laws of clay-water systems are not constant for all moisture contents; however, errors introduced from this source are usually of considerably less magnitude than normal variation in forest and range soils.

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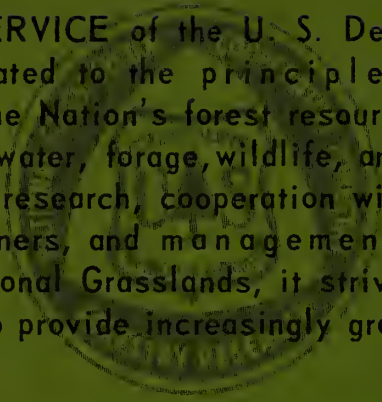
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